Quantum-Dot Laser Coupled Bowtie Antenna

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Abstract: The purpose of this paper is to introduce the idea of how an antenna can be coupled with a mode-locked quantum-dot (QD) laser chip to radiate in the microwave region. A brief theory of operation for the reconfigurable mode-locked quantum-dot laser is first explained and the design of the waveguide and antenna part is next presented. Due to its wide frequency bandwidth, a bowtie antenna is coupled to a QD laser. The goal is to achieve a THz radiator design by coupling the pulsing laser to a reconfigurable fractal antenna capable of radiating at THz frequency. We present a preliminary design that includes antenna simulations and their comparison with measured data. The challenges associated with integrating the antenna with the quantum-dot laser are also presented and discussed.

Introduction

The main emphasis of this paper is the design of a broadband antenna that is fed by a quantum-dot mode locked laser (QD-MLL) [1]. The ultimate object is to realize THz radiation at different frequencies with the QD-MLL.

Quantum Dot Mode Locked Laser: The source of radiation, at the present stage, is the single mode-locked quantum-dot laser that can be tuned to operate at different pulsed repetition rates by varying its cavity length. A general diagram of a laser chip is shown in Figure 1. The quantum dot mode-locked laser (QD-MLL) was fabricated from a multi-stack laser structure following standard multi-section device processing [2, 3]. A reconfigurable multi-section device consists of a single-mode ridge waveguide divided into electrically isolated sections that can be biased independently. By altering the bias on each section, the QD-MLL can achieve harmonic mode-locking at multiples of the fundamental frequency. The 11-section device fabricated, operates from 7.2 GHz to 50.7 GHz [4].

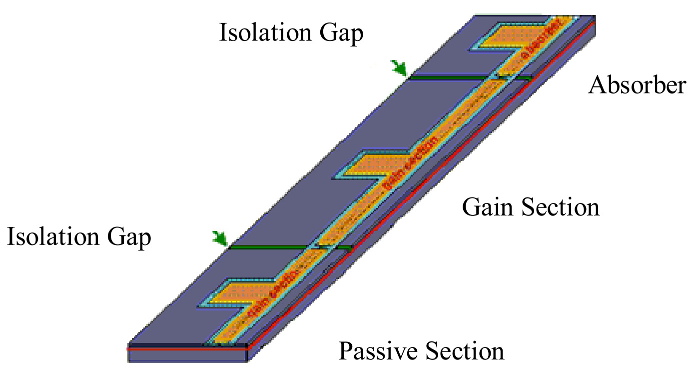

Fig 1, 3-Section Quantum Dot Passively Mode-Locked Laser Device Layout

A coplanar slot (CPS) line connects the bowtie antenna to the quantum-dot laser chip. The determination of the CPS line dimensions are presented later in this paper. In the quantum-dot laser chip structure, the bottom plane of QD-MLL represents the ground while the photocurrents are emitted from the top surface of the absorber section of the laser chip. The bottom-side of the QD-MLL is directly connected to one of CSP lines. The top plane is connected to the other CPS line by gold wire bonding.

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Since the QD-MLL is conceptually in the form of a waveguide structure, composed of semiconductor materials (GaAs/InGaAs), its impedance is very high. To avoid any inevitable mismatching problem between the antenna and the QD-MLL, a broad bandwidth antenna is suggested in this research. Here a bowtie antenna is chosen due to its broadband bandwidth and its flexibility in attaching various CPS lines to it.

Antenna Design: In this section, the design of the antenna and the associated coplanar waveguide required to efficiently couple to the optical source is presented. The universal diagram of the photonic and the RF element is shown in Figure 2. The microwave pulses are routed by the coplanar waveguide to the bowtie antenna.

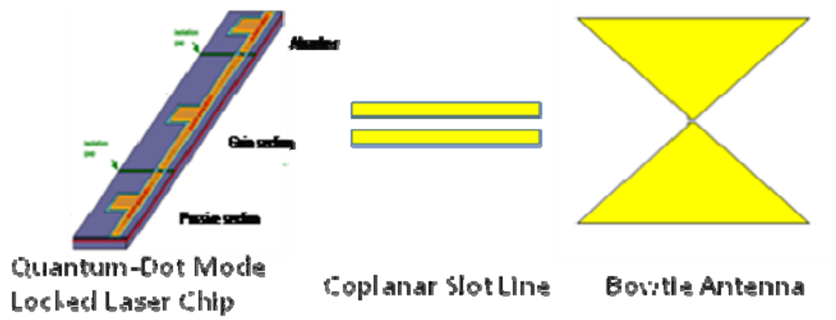

Fig 2, Schematic of the QD-MLL coupled bowtie antenna

By simply mounting the QD-MLL on one of the two CPS lines, the bottom contact between the QD-MLL and the line is accomplished. The signal pulse from the top plane of the laser chip can be linked to different CPS lines with a gold bond-wire at this stage. The impedance of a line is designed to be 50 [Ω] which depends on the line width and gap between the two lines. Our initial design yielded CPS lines with 160μm in width and a gap of and 20μm to achieve the required 50[Ω] characteristic impedance.

The bowtie antenna structure is defined by its flare angle and bow length. The quasi-static impedance is defined by equation (1). Figure 3 shows Z_{qs} as a function of the flare angle for different substrates. The flare angle is set to 90˚ for this case [6].

$$Z_{qs} = \frac{120\pi}{\sqrt{\varepsilon_{eff}}}\left[\frac{K(k)}{K(k')}\right] \quad [\Omega] \qquad (1)$$

where $\varepsilon_{eff} = \frac{1}{2}\left(\varepsilon_{r,GaAs} + 1\right)$, $k = \tan^2\left(\frac{\pi}{4} - \frac{\theta}{4}\right)$, $k' = \sqrt{1 - k^2}$ and θ is a bow angle.

Another antenna variable that has to be defined is its bow length. In Figure 4, the S-parameters are plotted as a function of operating frequency for various bow lengths. The antenna structure consists of a 90˚ flare angle and a 20μm gap between the two electrically isolated bows. A GaAs layer with a 400μm thickness is used as a substrate. For an 8 GHz operation a bowtie antenna, a 3700μm long bow and a 20μm gap between bows is designed. The associated coplanar slot line has the dimension of 160μm in width and a gap of 20μm. The *Ansoft HFSS* simulator is used to simulate the bowtie antenna [6].

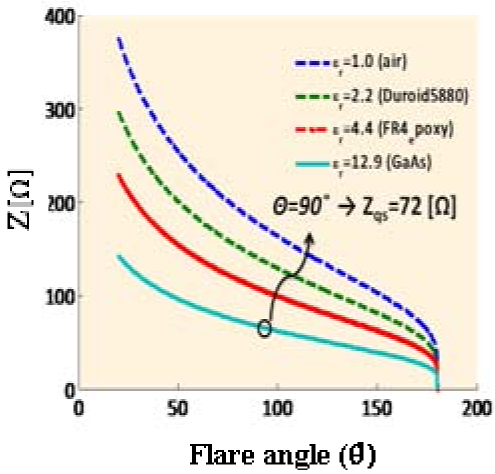

Fig 3, Z_{qs} as a function of the antenna flare angle for different substrates

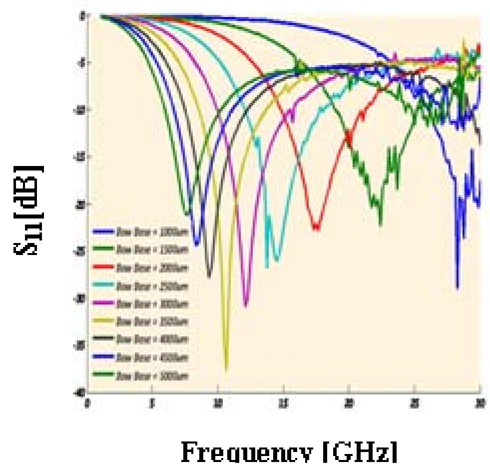

Fig 4, S_{11} of bowtie antenna as a function of operating frequency for various bow lengths

Antenna Matching: One of the most challenging parts in our design is resolving any mismatches when we integrate the optoelectronic source and the microwave device. As the quantum-dot laser chip is made up of semiconducting materials, its impedance is measured around 500 [Ω] up to 1 [KΩ]. The computed antenna impedance is 72[Ω] as shown in Fig 3. The impedance difference of the two devices certainly degrades the signal flow and thus a matching network is required. To implement the matching network, the equivalent circuit model of an individual element needs to be defined. Figure 5 presents the circuit model of the antenna, the quantum-dot laser diode, and the matching network. In the model, the equivalent lumped components of a bowtie antenna are its radiation resistance (R_{rad}), antenna resistance (R_a) and reactance (X_a). Likewise, those of the QD-MLL are a bond-wire's inductance (L_{per}), capacitance (C_{per}), sheet resistance (R_s), laser impedance (R_j), and junction capacitance (C_j), respectively. Among various matching networks, the binomial multisection transformer is first chosen. The result and other trial of matching will be presented and discussed.

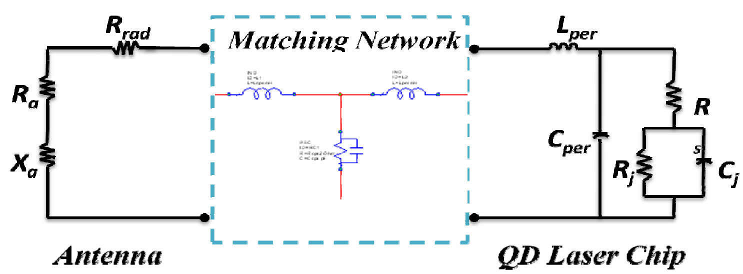

Fig 5, Equivalent circuit model

Fabrication: As a start, the coplanar bowtie antenna, the CPS lines and the single mode-locked laser are fabricated, separately. A thick layer (400μm) of GaAs was chosen as a substrate, followed by a layer of negative photoresist (IR 5214E-IR). Using a photo-lithographic approach, a coherent UV laser beam (3rd harmonic of a YAG laser at λ=405nm) was used to define the bowtie antenna image in the PR layer. Next an e-beam metal evaporation was used to deposit a thin film of Ti and Au (30nm) atop the PR layer, followed by a lift-off process using acetone to remove the PR. The total size of a device is less than 1cm.

Results: Two S_{11}-measurements are presented here. In Fig 6, the antenna is fabricated when the exposure and development times where 10sec and 30sec respectively. In Figure 7, the exposure and development times where increased to 50sec and 35sec, respectively. The measured data show good agreement with simulations.

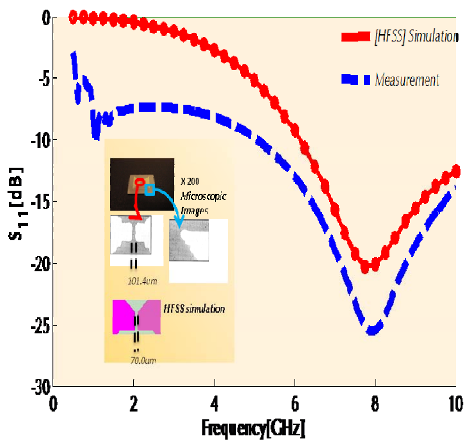

Fig 6, Comparison of simulated and measured S_{11} with exposure time of 10sec and development time of 30sec.

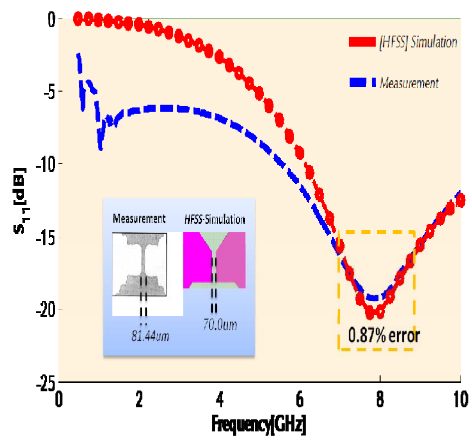

Fig 7, Comparison of simulated and measured S_{11} for exposure time of 50sec and development time of 35sec.

Conclusion

The first bowtie antenna coupled with a QD-laser chip is introduced. The bowtie antenna is shown in Fig 6-7, with a bow angles of 90 ˚and its total length of 7.6mm, and is intended to operate around 8GHz. The measured S_{11} shows a good agreement with the simulation result. The impedance matching network based on a simple equivalent circuit model is presented in Fig 5. A complete discussion about the design of the bowtie antenna and its matching to the quantum dot laser chip will be presented.

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